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The KneeKG system: a review of the literature

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Abstract

Purpose Accurately quantifying knee joint motion is not simple. Skin movement over the medial and lateral femoral condyles is the greatest obstacle to obtaining accurate movement data non-invasively. The KneeKG$^{\text{TM}}$ system was developed with the objective of providing high reliability movement analysis. The goal of this manuscript is to review the technical details, clinical evidence, and potential applications of this system for evaluation of rotational knee laxity.

Methods A comprehensive review of the MEDLINE database was carried out to identify all clinical and biomechanical studies related to KneeKG$^{\text{TM}}$ system.

Results The KneeKG$^{\text{TM}}$ system non-invasively quantifies knee abduction/adduction, axial rotation, and relative translation of the tibia and femur. The accuracy and reproducibility of the system have been assessed. The average accuracy of the acquisition is 0.4° for abduction/adduction, 2.3° for axial rotation, 2.4 mm for anteroposterior translation, and 1.1 mm for axial translation. This clinical tool enables an accurate and objective assessment of the tri-planar function of the knee joint. The measured biomechanical parameters are sensitive to changes in gait due to knee osteoarthritis and ACL deficiency.

Conclusion The KneeKG$^{\text{TM}}$ system provides reliable movement analysis. This system has the potential to improve understanding the biomechanical consequences of trauma or degenerative changes of the knee as well as more accurately quantify rotational laxity as detected by a positive pivot-shift test.

Keywords Knee · Movement analysis · KneeKG · Rotational laxity

Introduction

In order to diagnose and provide effective treatment for knee conditions, knee pathomechanics must be accurately described [28]. Evaluation of the success of interventions requires consistent and accurate evaluation of pre- and post-operative knee joint motion. While significant information can be obtained through the manual clinical examination, more precise and objective tools are quite useful [3], particularly in regard to assessment of rotational laxity.

The majority of clinical tools available for evaluation of joint laxity have significant limitations such as the ability to analyze in only one or two dimensions and limitations of their precision and reproducibility [1, 2, 7, 13, 19, 23]. A number of assessment tools frequently utilized in orthopedic research (pivot-shift analyzer [16], various rotatory assessment devices [3, 19], gait assessment [27]) meet these requirements of precision, reproducibility, and objectivity that are often lacking in manual examination. In

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spite of these advantages, adaptation of such techniques from the laboratory into clinical practice has been slow and difficult, particularly in regard to gait analysis [29].

The KneeKG^{TM} system was developed with the aim of making biomechanical assessment of the behavior of the knee joint during gait a part of routine clinical care. The goal of this manuscript is to review the technical details, clinical evidence, and potential applications of this system for evaluation of rotational knee laxity.

Design

The development of the KneeKG^{TM} began in 1992 through efforts at the Imaging and Orthopaedics Research Laboratory in Montreal, Canada, to better understand the impact of tunnel positioning on ACL graft elongation, torsion, and bending. The idea was that in order to adequately assess the behavior of the ACL graft during functional activities, one had first to be able to evaluate three-dimensional (3D) knee kinematics in vivo. After reviewing the available scientific literature, they came to the conclusion that no assessment device or methodology at the time could be used to accurately quantify knee biomechanics in three dimensions.

Because skin motion artifact is a major factor in the precision of measurements of knee joint motion, design for the new system began with a quantification of the skin-bone movement around the knee [26]. Based on this study, the group developed a harness to be fixed quasi-statically on the thigh and calf, therefore reducing the skin motion artifact [25]. This harness was shown to be accurate in obtaining 3D kinematic data that could be used to evaluate ACL and ACL graft deformation in vivo [24, 25].

The potential of the device to assess 3D knee kinematics in a variety of situations led to the commercialization of the device under the name KneeKG^{TM}. The device allows a quick (20 min) assessment of knee kinematics. Patient examination can be performed in a small assessment room with a treadmill. Software has been designed to process and automatically generate biomechanical reports enabling its use in the clinical setting.

Validation

The essential step in validating the accuracy of the KneeKG^{TM} device was determining how accurately the non-invasive skin markers utilized by the system represent the motion of underlying bones. The accuracy of this semi-flexible attachment system design was evaluated by Sati et al. [25] by comparing measurements obtained with the attachment system to actual bony motion as assessed with calibrated fluoroscopy. They demonstrated that within a 65° arc of motion, the system could measure knee kinematics with an average accuracy of 0.4° of knee abduction and adduction, 2.3° for axial rotation, 2.4 mm for anteroposterior translation, and 1.1 mm for axial translation. It should be noted that this level of precision likely represents the best-case scenario and may not reflect actual clinical results.

Analysis of the shortcomings of the initial design led to the development of a new exoskeleton attachment system. The accuracy of this new system to capture small knee movements was assessed through similar fluoroscopic studies [6]. The experiment was set-up to determine the improvement in accuracy of assessing motion of the underlying bone with the exoskeleton relative to attachment of markers directly on the skin. The results demonstrated that errors were reduced by a factor of 4.3–6.2 on average when the exoskeleton attachment was used. The accuracy of this system was assessed by Hagemeister et al. [9]. On 16 healthy subjects, they found intra-patient reproducibility between 0.86 and 0.97 for abduction/adduction, internal/external rotation, and flexion/extension movements. In a different study, Hagemeister et al. [10] determined the mean repeatability of measures to range between 0.4° and 0.8° for knee rotation angles and between 0.8 and 2.2 mm for translation. It should be again noted that this level of precision likely represents the best-case scenario and may not reflect actual clinical results, especially in cases of extremes of body habitus or motion patterns.

The intra- and inter-observer reliability of the attachment system for recording 3D knee kinematics during gait was determined recently by Labbe et al. [17]. Their data showed that the 3D kinematics measurements are highly reliable (intra- and inter-rater) with intra-class coefficient (ICC) values ranging between 0.88 and 0.94 for knee flexion/extension, abduction/adduction, and internal/external tibial rotation. A cadaveric study showed that the attachment system accuracy was more than sufficient to predict ACL bending and torsion deformations in vivo [24].

In a comparative study of three non-invasive attachment systems (a system involving wand-projected tripods on the thigh and calf [8], the KneeKG^{TM}, and a system consisting of hard plastic monoblocs attached to the femur and tibia [20]) [31], the authors utilized a low-dose biplanar x-ray system to evaluate the displacement of different attachment systems after 50 gait cycles. The authors concluded that the KneeKG^{TM} attachment system had the most stable attachment. The study highlighted that motion in the transverse plane was relatively poorly controlled with all attachment systems.

Fig. 1 Anterior view of a right knee fitted with the KneeKG tracker system. Secure fixation to the thigh and calf minimizes skin motion artifact

Data Collection

The KneeKG™ is composed of passive motion sensors fixed on the validated knee harness described above (the KneeKG™ 3D-Tracker) (Fig. 1), an infrared motion capture system (Polaris Spectra camera, Northern Digital Inc.), and a computer equipped with the Knee3D™ software suite (Emovi, Inc.). The camera and computer can both be mounted on a cart making the entire system mobile (Fig. 2). The system measures and analyses the 3D position and movement of the patient's knee.

During the KneeKG™ exam, the patient must wear shorts. Following application of the KneeKG™ tracker, a calibration procedure as described by Hagemeister et al. [10] is performed to identify joint centers (hip, knee, ankle) and define a coordinate system on each body segment (e.g., femur and tibia). The acquisition protocol takes between 15 and 20 min when performed by a trained technician. All movements are captured at a frequency rate of 60 Hz by the infrared camera. Because treadmill walking can be unfamiliar, a treadmill walking habituation period between 6 and 10 min should be initiated prior to data collection to ensure reproducible 3D kinematic data [21, 35]. Trials are then recorded at the patient's comfortable treadmill gait speed over 45 s (Fig. 3). During data collection, 3D bone reconstruction models (tibia and femur) are displayed on the monitor, allowing a real-time visualization of the 3D knee movements (Fig. 4). Different gait conditions can be recorded sequentially and compared, such as slow and fast pace walking, and walking with or without shoes or orthotics.

Fig. 2 The KneeKG™ is composed of an infrared motion capture system (Polaris Spectra camera, Northern Digital Inc.) and a computer equipped with the Knee3D software suite (Emovi, Inc.). The camera and computer can both be mounted on a cart making the entire system mobile

Once data collection is complete, the user confirms where the gait cycle begins and confirms the automatic deletion of outliers. A report highlighting biomechanical deficiencies in all three planes of movement and during sub-phases of the gait cycle is generated automatically.

Clinical Applications

The object, visual assessment of knee joint motion provided by the KneeKG™ system may be useful in associating symptoms with specific abnormal gait mechanics. Further, the contribution of abnormal static knee laxity noted in classical, manual exams (Lachman, pivot shift, varus, and valgus stress) to dynamic knee stability during gait may be quantified. The visual output and objective numeric data may also facilitate patient education about the etiology and treatment of specific conditions. The ability to

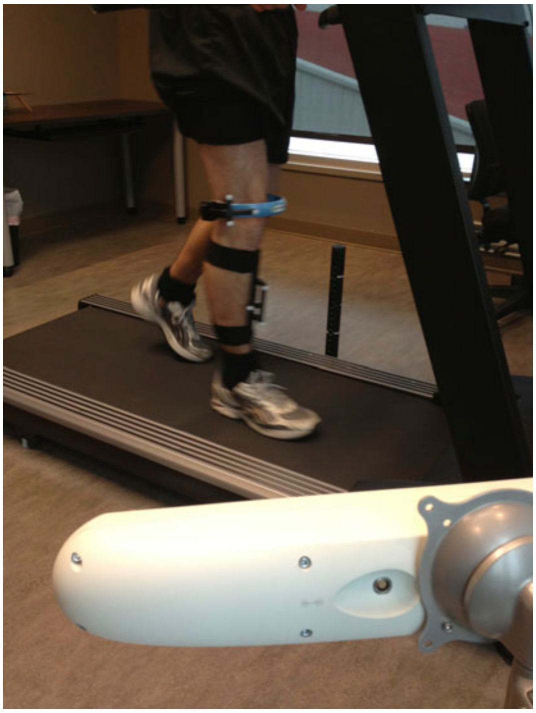


Fig. 3 Trials are recorded at the patient's comfortable treadmill gait speed. Different gait conditions can be recorded sequentially and compared

superimpose trials (i.e., pre- vs. post-treatment or pathological knee vs. contralateral knee) further facilitates these aims. Several published studies demonstrate the capacity of this system to assess knee function in cases of both ACL deficiency and osteoarthritis.

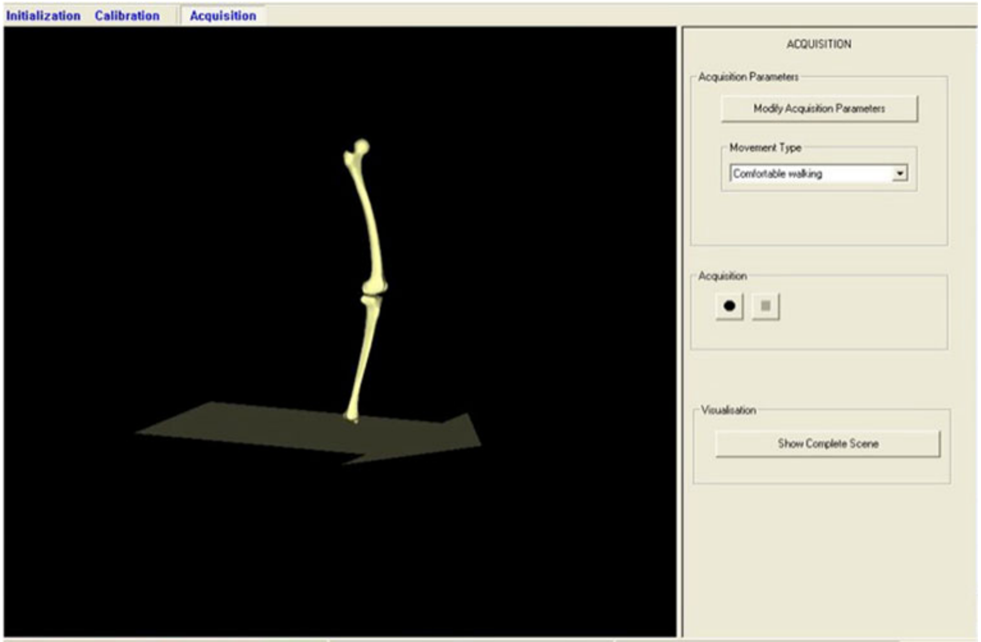
Quantitative assessment of laxity in cases of ACL deficiency

The precise quantitative rotational data provided by KneeKG^{TM} make it a suitable tool for evaluation of risk factors for ACL injury. This technique was demonstrated in a study evaluating the effects of ski binding parameters on knee biomechanics [30]. The authors evaluated the effect of the position of the binding pivot point and binding release characteristics on ACL strain during a phantom-foot fall during skiing. They concluded that a binding with two pivot points might reduce the occurrence of ACL injuries in skiers.

The system has also been utilized to assess residual knee laxity following ACL reconstruction. Fuentes et al. [5] demonstrated through 3D knee biomechanical analysis that altered knee kinematics is present after an ACL injury. They hypothesized that such residual deficits, if still present post surgery, may explain why some patients do not return to their pre-injury level of activity [5].

Work by Hoshino and Tashman has demonstrated that increased tibial internal rotation during running is associated with increased sliding in the medial tibiofemoral joint [12]. Fuentes et al. [4] used the KneeKG^{TM} system to evaluate gait adaptation undertaken by chronically ACL-deficient patients to avoid anterolateral rotatory knee instability. They hypothesized that during the terminal stance phase of the gait cycle, ACL-deficient patients would exhibit reduced tibial internal rotation moments and higher knee flexion angles. They were able to demonstrate

Fig. 4 During data collection, 3D bone reconstruction models (tibia and femur) are displayed on the monitor, allowing a real-time visualization of the 3D knee movements



Movement Type: Comfortable walking

that patients did adopt this “pivot-shift avoidance” gait, possibly to prevent anterolateral rotatory knee instability.

Quantitative assessment of laxity in cases of osteoarthritis

Turcot et al. [32] demonstrated that the KneeKG^{TM} system could discriminate between medial osteoarthritic and asymptomatic knees during gait. They demonstrated the potential of the system to provide new parameters that could be used in the quantification of knee instability and altered load transmission associated with degenerative change. A follow-up study determined the responsiveness of these parameters in assessing changes in joint stability and load transmission following a rehabilitation treatment [33]. This study demonstrated that a 3-month treatment protocol combining physical therapy and an exercise program decreased anteroposterior knee laxity and normalized load transmission during gait. They found high sensitivity of these parameters to changes in gait after treatment. A further study with the KneeKG^{TM} system highlighted greater knee joint laxity during the performance of a monopodal stance task in patients with osteoarthritis [34].

Applications for quantitative analysis of the pivot shift

The pivot-shift examination relies heavily on the clinician’s experience and is known to have poor repeatability, especially for less experienced clinicians [22]. A quantitative assessment of pivot-shift finds would thus be desirable. In a preliminary study, Labbe et al. [15] noted acceleration and velocity of tibial translation to be most beneficial for quantitative assessment of the pivot shift. Other authors have confirmed the utility of assessment of the acceleration of tibial translation in detecting ACL insufficiency [11, 18].

A study then was undertaken to objectively grade the pivot shift based on recorded knee joint kinematics [16]. Fifty-six subjects with different degrees of knee joint laxity had the pivot-shift test performed by one of eight different orthopedic surgeons while their knee joint kinematics were recorded. The data and a support vector machine–based algorithm were used to objectively classify these recordings according to a clinical grade. There was substantial agreement between the grade presented by the system and the surgeons (weighted $\kappa = 0.68$). Seventy-one of 107 recordings (66%) were given the same grade and 96% of the time they were within one grade. Moreover, grades 0 and 1 were distinguished from grade 2–3 with 86% sensitivity and 90% specificity. Their results showed the feasibility of automatically grading the pivot shift in a manner similar to that of an experienced clinician, based on knee joint kinematics.

The next step was to find a method to lessen the variability attributable to clinician technique, therefore increasing inter-grade differences [14]. Three different orthopedic surgeons each performed the pivot shift test on 12 subjects. Knee joint kinematics were recorded using electromagnetic motion capture devices. Inter-clinician variability was quantified and a method was developed to diminish it using the angular velocity of flexion. This method was then applied to a larger population composed of 127 knees with various degrees of instability, evaluated by one of eight different orthopedic surgeons. Normalization of kinematic parameters using the angular velocity of knee joint flexion produced by the clinicians reduced the inter-clinician variability by 20%, resulting in an intraclass correlation coefficient (ICC) of 0.52, up from 0.41 before normalization. These results suggest that this method may become a reliable tool allowing objective measurement of the pivot-shift phenomenon, although further studies are mandatory to assess its practical interest.

Conclusion

The non-invasive fixation devices used by the KneeKG^{TM} system and other systems to evaluate the rotational laxity appear to provide an objective assessment of the precise biomechanical behavior of the knee. These systems have the potential to improve understanding the biomechanical consequences of trauma or degenerative changes of the knee as well as more accurately quantify rotational laxity as detected by a positive pivot-shift test.

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